

# **The Predictability of Large-Scale, Short-Period Ocean Variability in the Philippine Sea and the Influence of Such Variability on Long-Range Acoustic Propagation**

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## **LONG-TERM GOALS**

The long-term goal of this project is a complete and accurate understanding of the properties of acoustic pulses sent over mesoscale to global scales. In particular, I want to understand the forward problem for calculating travel times of the early ray arrivals and late mode arrivals in long-range acoustic transmissions and to understand the sampling associated with those arrivals. The better the understanding of the forward problem, the better acoustic data can be used to understand the ocean.

## **OBJECTIVES**

This work aims to develop models of ocean variability for understanding and predicting long-range acoustic propagation. Models of ocean variability, and therefore the associated sound speed variability, in the Philippine Sea are to be developed from historical data and from the PhilSea'09 and PhilSea'10 experiments, or adapted from existing efforts. Emphasis is placed on distinguishing between predictable (mesoscale, internal tides) and stochastic (internal waves) variabilities. These models will be used to obtain the relevant acoustic properties (e.g., full-depth sections of sound speed) such that the effects of variability on long-range acoustic propagation can be calculated and compared to field data. The work therefore aims to develop models for the physical oceanography of the central Philippine Sea with accurate and verified acoustical and oceanographic properties and with a quantified assessment of the predictability of the various model components.

## **APPROACH**

The general approach to better understanding acoustic propagation is a careful processing and study of acoustic data obtained on line arrays of hydrophones from acoustic propagation of over 100-5000 km ranges, acquired as part of the larger North Pacific Acoustic Laboratory (NPAL), the Philippine Sea Experiment, and the Norwegian ACOBAR (Fram Strait) collaborations in the present case. These experiments have been conducted primarily by Peter Worcester and his group at the Scripps Institution of Oceanography, while the ACOBAR tomography work has been led by Hanne Sagen from the Nansen Center in Bergen, Norway. Long-range acoustic data are often analyzed in combination with other complementary in situ data that may be available, such as from thermistors or satellite altimetry. Regional or global ocean models have also been very useful in understanding the various influences on

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acoustic propagation. The general aim has been to use the acoustic data to test and improve such models. These models or state estimates do not resolve the ocean down to the internal waves scales that affect the acoustic propagation, however. If such models are data assimilating, then they provide an optimal synthesis of the available in situ data. This synthesis is usually better than can be obtained by considering the data in isolation. Indeed, the optimal test of acoustic data, in situ data, and ocean models is through the combination of all these elements by data assimilation, which simultaneously tests the observations against the physical or acoustical model in a systematic and self-consistent way while reconciling the disparate data types. The modeling and state-estimates from the Estimating the Circulation and Climate of the Ocean (ECCO) group at the Jet Propulsion Laboratory have been used for these purposes; my collaborator with that group is Dimitris Menemenlis.

## **WORK COMPLETED/RESULTS**

The recent years of this project have involved several activities and lines of research. The various facets of this project are summarized here.

**Philippine Sea Tomography.** Processing and analysis of the data collected during PhilSea'09 and PhilSea'10 is still ongoing, hence definitive results cannot yet be stated. It appears that the mode-1 internal tides of the region, including semidiurnal and diurnal constituents, are vigorous and highly coherent in time. Some degree of predictability is indicated from the comparisons of the in situ observations with the altimetry analysis (Dushaw 2006; Dushaw et al. 2009), but the precise nature of this predictability is not yet clear. We are working toward assessing whether accurate predictions of the mode-1 internal tides - amplitude and phase at arbitrary points and time – can be obtained within the Philippine Sea basin, much like the barotropic tide is predicted now.

**The Time-Mean State of Ocean State Estimates and Long-Range Acoustic Propagation.** In many cases the time-mean state of ocean models is so erroneous as to give completely unphysical results for predicted acoustic time fronts. The time-mean of troublesome models can be replaced by that from the World Ocean Atlas (Antonov et al. 2006, Locarnini et al. 2006), under the assumption that even if the mean state of a model was erroneous, it still reasonably predicts ocean variability (Dushaw et al. 2009). The World Ocean Atlas has always produced time fronts that compare reasonably well with measured data, so we conjectured that calculating and comparing acoustic patterns in the time mean of models can produce a reasonable zero-order test of model fidelity to the "true" state of the ocean (Dushaw et al. 2013).

Paraphrased from the paper (Dushaw et al. 2013):

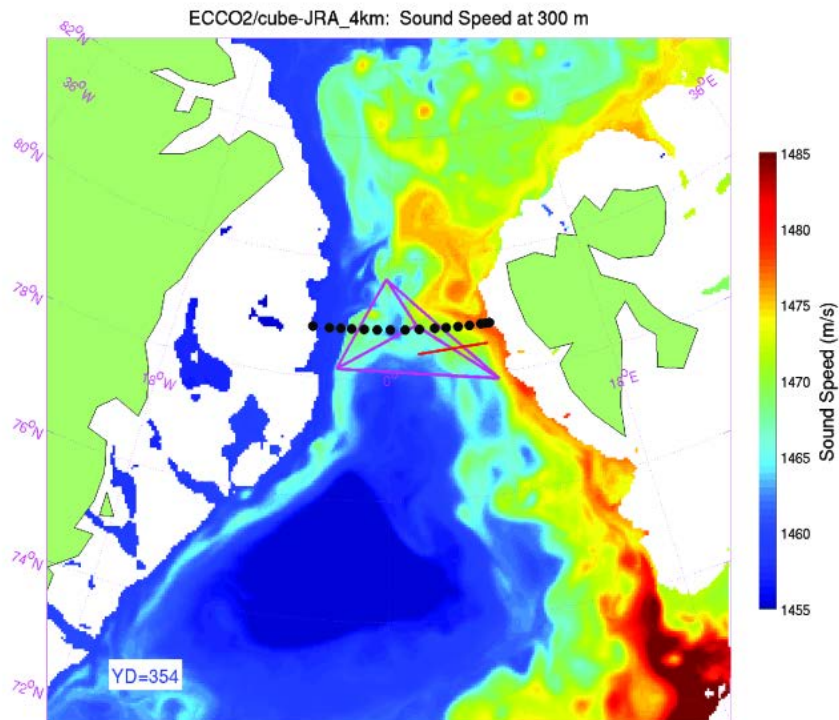
It is natural to contemplate which realization for the ocean's mean state is “best”, but the question both demands and defies better definition. By “best”, one must ask, “best for what purpose”? The World Ocean Atlas is a highly-smoothed map of observations that span several decades, whereas the ECCO2 state estimate (Cazes-Boezio et al. 2008), for example, is a time-evolving description of ocean circulation constrained by both observations and model dynamics and thermodynamics. Errors in model parameterizations will result in an ECCO2 solution that cannot fit the available observations as well as the World Ocean Atlas can. But inasmuch as it is evident that the ocean is undergoing constant changes at every time scale, a climatological mean is an ill-defined concept and the World Ocean Atlas will suffer biases due to temporal and spatial sampling inhomogeneities. One approach for computing a climatological mean, while avoiding

sampling biases, is to base it on a time average of a state estimate, e.g., as was done by Forget (2010). Since the acoustic observations were made in specific years in the 1990's, do they comprise an accurate benchmark for the climatological mean? We think the aim here is just to show that any realization for the ocean's state, purporting to have a degree of realism in any particular region, is constrained to a fairly-well defined thermal structure. The acoustical comparisons suggest that the ranges for physical temperatures and temperature gradients are narrowly constrained.

Dushaw et al. (2013) argued that ocean models that do not give reasonably, “within the ballpark” predictions for acoustic time fronts do not accurately represent basic ocean structure, and further suggested that ocean models should be able to reproduce acoustic arrival patterns at least as well as the World Ocean Atlas. This constraint is not particularly stringent, but it nevertheless reflects the fact that the thermal structure of the ocean is basically stable and well defined. This property, reflected in a stable, well-defined sound channel, appears to me to be one of the minor miracles of nature. The relatively good agreement of the acoustic data with the more recent ECCO-MIT and ECCO2 solutions indicates that numerical ocean models have reached a level of accuracy where the acoustic data can provide useful additional constraints for ocean state estimation.

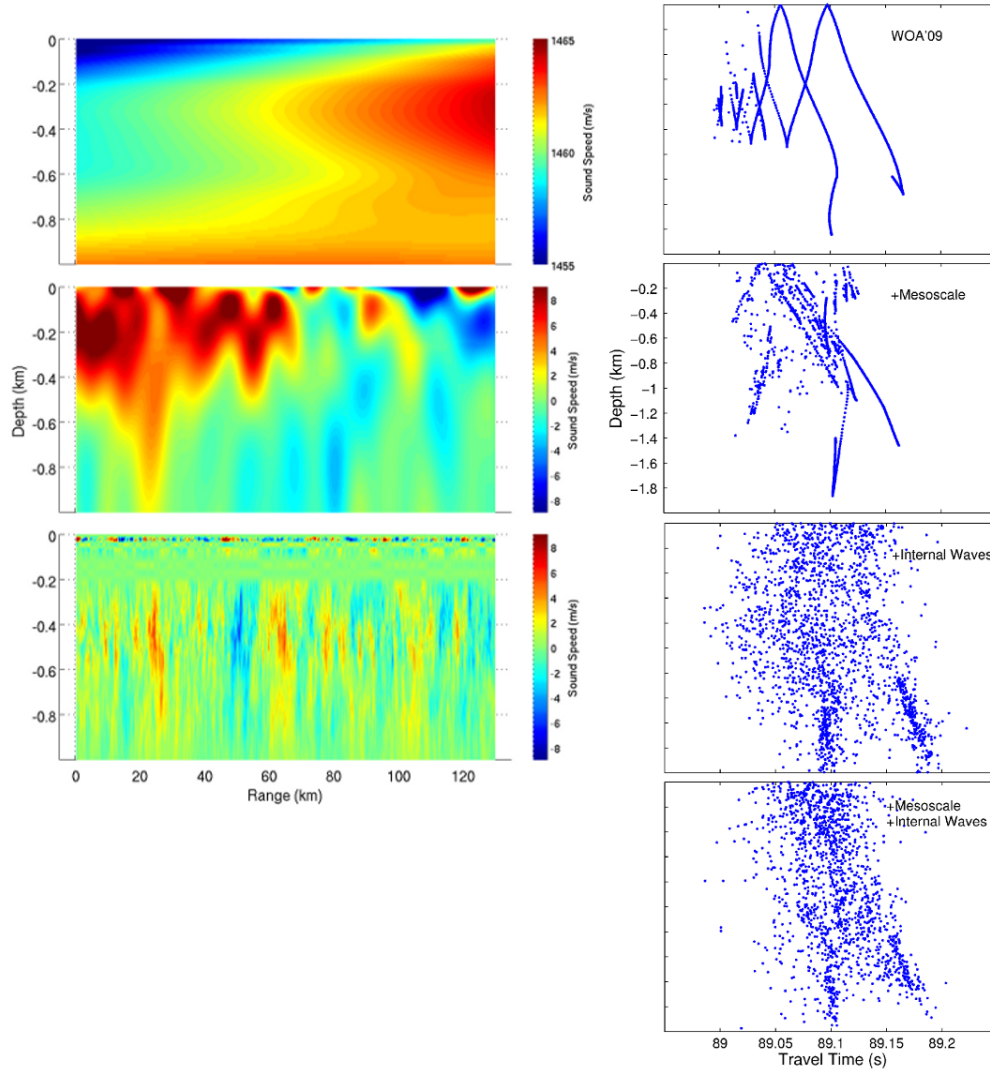
In the review process for this paper (Dushaw et al. 2013), it developed that at least some of our peers still view tomography as a problematic measurement. One reviewer cited complications stemming from horizontal refraction, effects of salinity, effects of ocean currents, non-linearity of acoustic propagation, and suspected errors with the ray approximation. The paper therefore included a section reviewing these small effects, drawing on research over the past 20-30 years, to show that such effects are inconsequential to the tomographic measurements. It may be worth noting that this researcher knows of no existing publication that shows that any such effects are of practical consequence.

**Tomography in Fram Strait** Part of this project was redirected toward research on acoustics and tomography within Fram Strait, with permission from the program manager. This section describes the results of research conducted during two visits during 2011-2 and 2013 to the Nansen Center in Bergen, Norway. Arctic waters are a challenging environment for acoustic propagation. The Arctic has unique characteristics of temperature and salinity, which vary considerably depending on region and depth. In addition, the presence of ice can complicate the properties of acoustic propagation. A careful study of the nature of acoustic propagation is essential for extracting the most information possible from acoustic data. A careful understanding of the acoustic conditions allows one to understand the acoustic data, and this understanding can then be exploited to obtain temperature, or other measurements of the ocean.



***Figure (Left) The sound speed at 300-m depth of Fram Strait at a particular time determined by an ECCO2 model. The DAMOCLES acoustic tomography path (red), the ACOBAR/UNDER-ICE tomography paths (magenta), and the sustained Fram Strait mooring line (black) are shown in Fram Strait between Svalbard and Greenland. The warm West Spitzbergen current flows northward off Spitzbergen before following topography eastward into the Arctic. Significant recirculation of warm water within Fram Strait is indicated, as is entrainment of this water into the southward East Greenland Current***

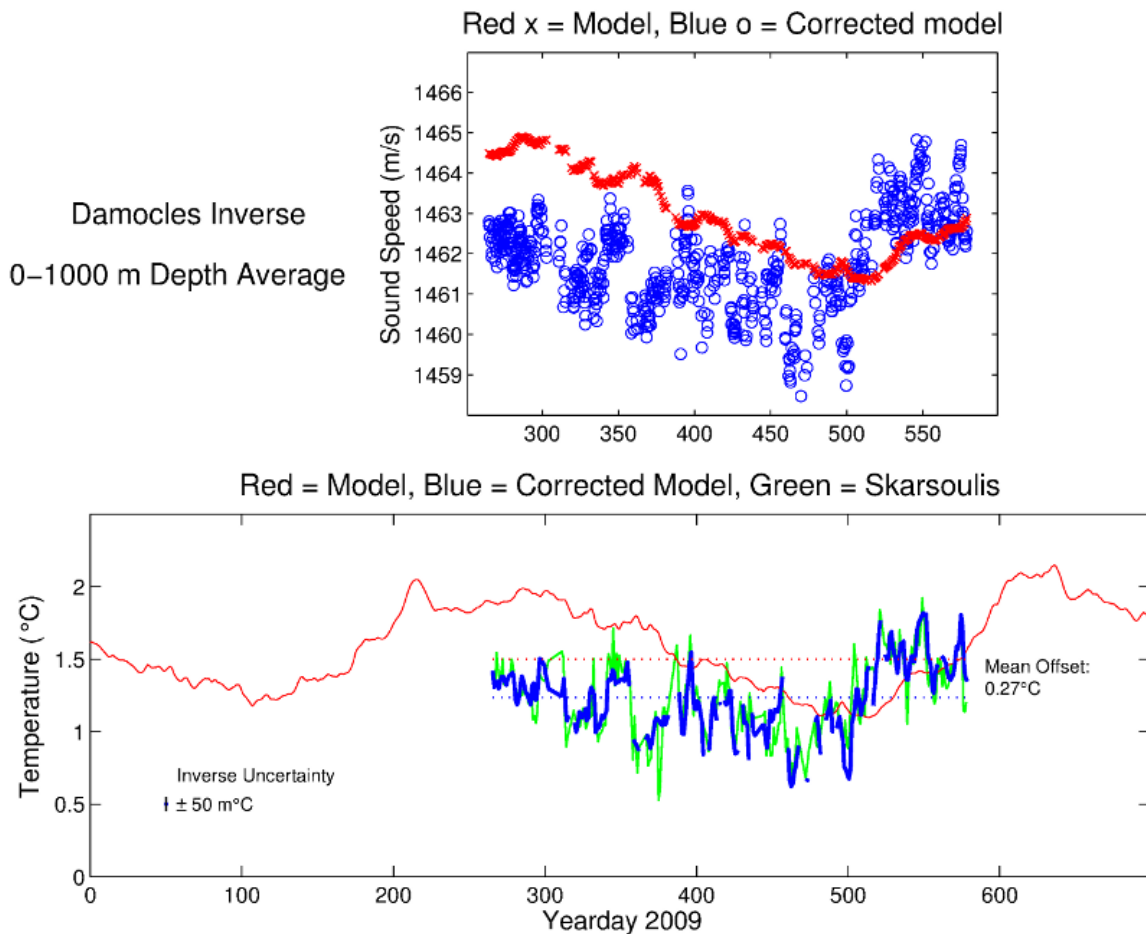
Arrival patterns recorded from the acoustic propagation along a 130-km path across Fram Strait (Figure) (DAMOCLES, a project conducted by Dr. H. Sagen of the Nansen Center) typically consisted of a single broad arrival pulse of about 100 ms width. The essential reason why these data had this characteristic was unknown. Such a pattern is not what is obtained in mid-latitude regions, where a dozen or so individual ray arrivals are resolved with about 10 ms precision. To better understand the nature of the acoustic receptions, simulations of mesoscale and internal wave variability were developed for the region. Computations of acoustic propagation through these simulations showed that the DAMOCLES arrival pattern was a result of two basic properties of sound speed. First, the climatological sound speed profile has weak vertical gradients near the sound channel axis, giving acoustic arrival patterns that are compressed in time. The dispersal of the usual "accordian" arrival pattern is weak, giving essentially a single arrival pulse (Figure). Second, the scintillations in sound speed caused by the mesoscale variability (O(20-km) length scales at this latitude) and internal waves caused a scattering or spreading of the arrival pulse of some 100-ms duration, consistent with the observations.



**Figure** Left, from top: Models for the top 1000-m of sound speed in Fram Strait along the DAMOCLES acoustic path: the climatological background with the core of West Spitzbergen Current centered on 300-m depth, simulated mesoscale variability, and simulated internal waves. Right, from top: Corresponding acoustic arrival patterns in depth vs travel time. The bottom panel closely corresponds to data. Small-scale variations of sound speed greatly influence the measured arrival pattern.

An inverse formalism, or objective map, was developed to obtain a simple, but quantitative, comparison of average temperatures as estimated by the mooring array across Fram Strait along 78°50' N and as estimated by tomography along the same section. The issue, of course, is the effect of noise from the ubiquitous small-scale mesoscale and internal-wave variations on the data used to obtain the estimate for the average. The moored array data gave an uncertainty for the average of  $\pm 0.073^{\circ}\text{C}$ , while the tomography data gave an uncertainty of  $\pm 0.053^{\circ}\text{C}$ . The combination of both data types gave an uncertainty of  $\pm 0.020^{\circ}\text{C}$ , starkly illustrating the complementarity of the data. Under the crude assumption of uncorrelated variations, if one were to employ only point measurements for this average, an order of magnitude more instruments would be required to achieve a comparable reduction in uncertainty.

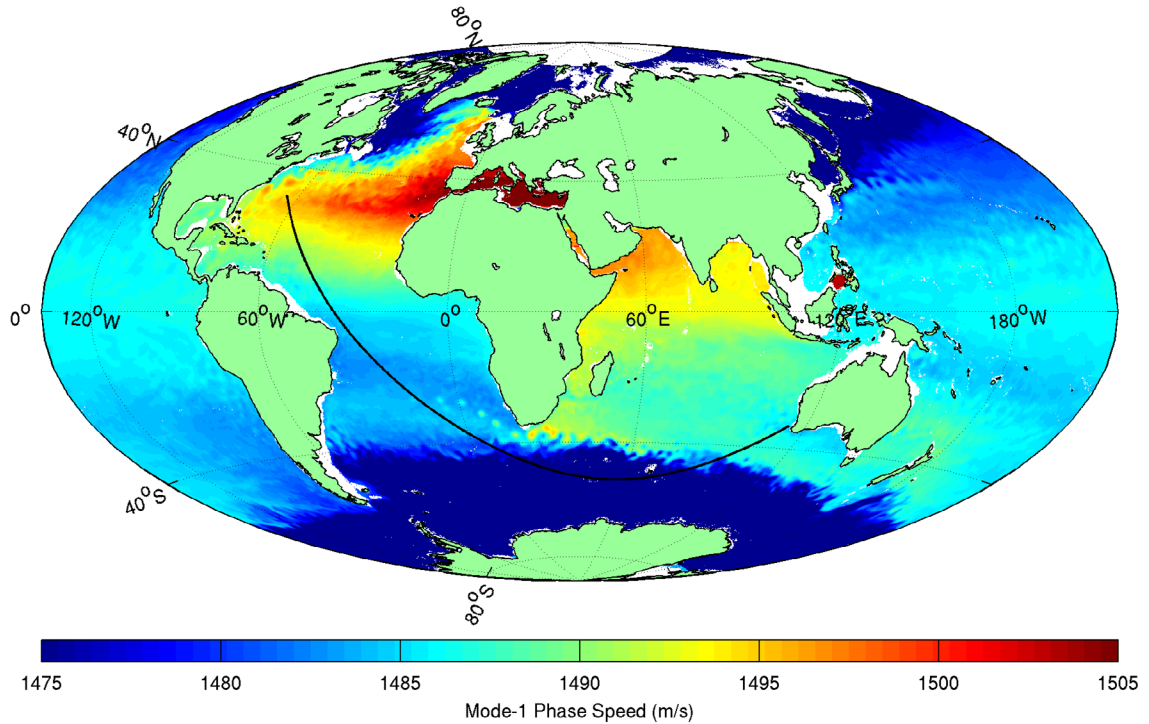




**Figure** (Top) Depth-averaged sound speed derived for the DAMOCLES tomography path from the 4-km resolution TOPAZ model (red) and from the use of acoustic data to correct the model (blue). The fluctuations in sound speed in the measurements are mostly caused by mesoscale variability within the West Spitzbergen Current. (Bottom) The depth-averaged temperature along the same path derived from the TOPAZ model (red) and by converting the inversion estimates for sound speed to temperature (blue). The green line denotes an inversion for the same quantity derived by Skarsoulis et al. (2010), and others by a completely different means; the agreement between the two disparate estimates is remarkably good. The data indicate that the time-mean model temperature is  $0.27^\circ\text{C}$  too warm.

**Antipodal Acoustic Thermometry: 1960, 2004** A recently completed study has updated analysis of historical acoustic data (Dushaw and Menemenlis 2013). Although this project was focused on this historical measurement of ocean climate and primarily supported by the National Science Foundation, the work drew on considerable research supported by the Office of Naval Research over the past 20 years. On 21 March 1960, sounds from three 300-lb depth charges deployed at 5.5-min. intervals off Perth, Australia were recorded by the SOFAR station at Bermuda (Figure). The recorded travel time of these signals, about 13,375 s, is a historical measure of the ocean temperature averaged across several ocean basins. The 1960 travel time measurement has about 3-s precision. High-resolution global ocean state estimates for 2004 from the “Estimating the Circulation and Climate of the Ocean, Phase II” (ECCO2) project were combined with ray tracing to determine the paths followed by the acoustic signals. The acoustic paths are refracted geodesics that are slightly deflected by either small-scale topographic features in the Southern Ocean or the coast of Brazil. The refractive influences of intense, small-scale oceanographic features, such as Agulhas Rings or eddies in the Antarctic

Circumpolar Current, greatly reduce the necessary topographic deflection and cause the acoustic paths to meander in time. The ECCO2 ocean state estimates, which are constrained by model dynamics and available data, were used to compute present-day travel times. Measured and computed arrival coda were in good agreement. Based on recent estimates of warming of the upper ocean, the travel-time change over the past half-century was nominally expected to be about minus 10s, but little difference between measured (1960) and computed (2004) travel times was found. Taking into account uncertainties in the 1960 measurements and in the 2004 ocean state estimates, the ocean temperature averaged along the sound channel axis over the antipodal paths has warmed at a rate less than 4.3 m°C/yr (95% confidence).



**Figure** *Acoustic mode-1 phase speed at 15 Hz derived from the ECCO2 cube78 state estimate for August 1993. The WGS84 geodesic path between the location of the Perth shots and the Bermuda SOFAR station receivers is indicated. The phase speed is a variable strongly dependent on ocean temperature; mode-1 phase speed variations follow those of ocean temperature near the sound channel axis. The large phase speed gradients of the Antarctic Circumpolar Current and the Agulhas Rings in the South Atlantic are evident. These features have the greatest refractive influence on the acoustic paths. Hammer-Aitoff projection.*

**Horizontal Refraction of Acoustic Tomography Signals** As a corollary to the work examining the horizontal refraction of antipodal acoustic signals (Dushaw and Menemenlis 2013), it was a simple matter to finally quantify the effects of horizontal refraction on basin-scale or regional acoustic tomography in a realistic ocean environment (Dushaw 2013). As expected, such effects are so small that they can be safely ignored in practice. While a signal for long-range acoustic tomography sent between a source and a receiver follows a refracted geodesic path, most often this path is approximated by geodesic path. Since the inception of acoustic tomography, this approximation has been justified from theoretical considerations relying on estimates of horizontal gradients of sound speed or on numerical simulations employing simple theoretical models. The horizontal refraction of long-range signals was re-examined by computing acoustic propagation through global ocean state estimates



obtained at 3-day intervals during 2004 from the Estimating the Circulation and Climate of the Ocean, Phase II (ECCO2) project. Basin-scale paths in the eastern North Pacific Ocean employed for the 1993-2003 Acoustic Thermometry of Ocean Climate (ATOC) program and regional-scale paths in the Philippine Sea employed for observations during 2010-2011 were used as examples. For basin-scale paths, refracted geodesic and geodesic paths differ by only about 5 km, although the precise refractive effects depend on path geometry with respect to oceanographic features. Refraction causes travel times to decrease by 5-10 ms, and azimuthal angles to deviate by about 0.2 deg. At regional scales in the Philippine Sea, paths deviate from the geodesic by only 250 m, and travel times are affected by less than 0.5 ms. Such effects are barely measureable and of little consequence for the analysis of tomographic data. Refraction details depend on mode number and frequency, hence the effects of horizontal refraction may contribute to the incoherence of acoustic signals.

## IMPACT/APPLICATIONS

The conclusions with respect to acoustic tomography indicate a transformative development for the world's ocean observing system. While the Argo profiling float system and satellite altimetry programs are at present the cornerstone of this global observing system, it is clear that the acoustical observations will be a valuable complementary addition to these elements, giving new insights into the nature of subsurface variability of the ocean at the largest scales (Dushaw et al. 2010). The strengths of the acoustic measurement are its inherent averaging properties which no other measurement type can match. It is also clear that these disparate data types can be synthesized in an objective, systematic way through data assimilation into ocean models. The latest ocean models have sufficiently realistic acoustical properties that they offer reasonable zero-order reference states for ocean acoustic tomography. There are no technical or theoretical impediments to implementing acoustic thermometry as part of the ocean observing systems. The present system of observations and modeling aims not only to understand ocean variability, but also to predict this variability over a variety of time scales; thermometry will be an important addition to the system for achieving these goals.

## RELATED PROJECTS

This project has been a contribution to the North Pacific Acoustic Laboratory (NPAL) collaboration, which comprises researchers from the Applied Physics Laboratory, the Scripps Institution of Oceanography, and the Massachusetts Institute of Technology, among others. (<http://npal.ucsd.edu/>)

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